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RF generation in the DARHT Axis-II beam dump

Carl Ekdahl

I. INTRODUCTION

We have occasionally observed radio-frequency (RF) electromagnetic signals in the downstream transport (DST) of the second axis linear induction accelerator (LIA) at the dual-axis radiographic hydrodynamic testing (DARHT) facility. We have identified and eliminated some of the sources by eliminating the offending cavities [1]. However, we still observe strong RF in the range 1 GHz t0 2 GHz occurring late in the ~2-μs pulse that can be excited or prevented by varying the downstream tune [2]. The narrow frequency width (<0.5%) (Fig. 1) and near exponential growth at the dominant frequency is indicative of a beam-cavity interaction, and electro-magnetic simulations of cavity structure show a spectrum rich in resonances in the observed frequency range [3]. However, the source of beam produced RF in the cavity resonance frequency range has not been identified, and it has been the subject of much speculation, ranging from beam-plasma or beam-ion instabilities to unstable cavity coupling.

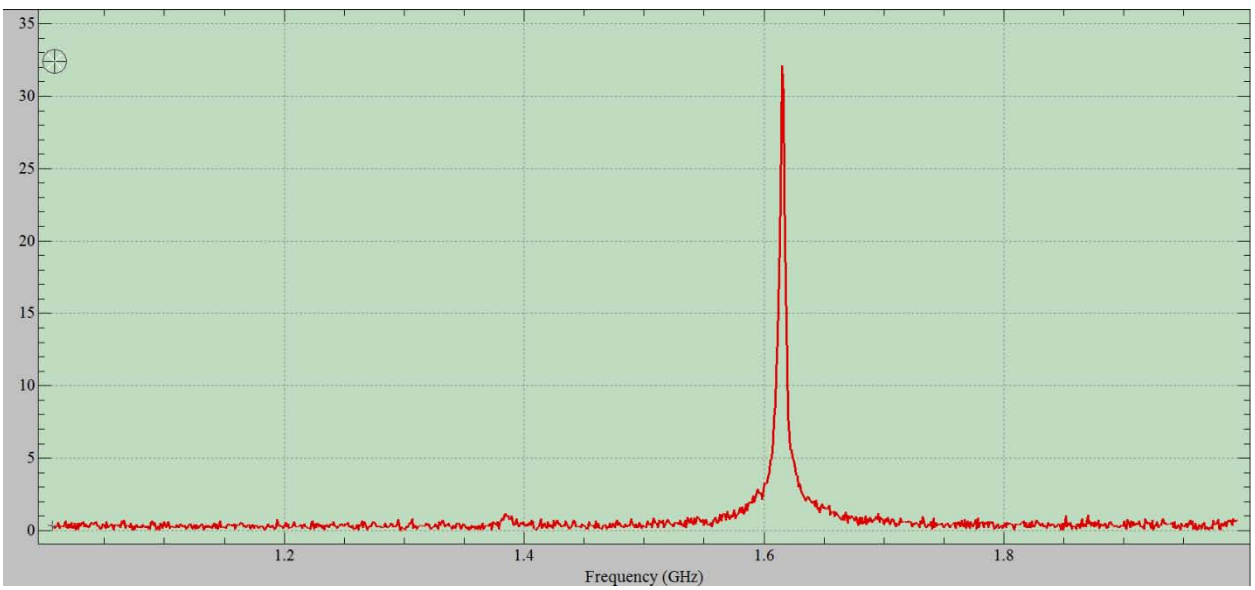

Figure 1: Amplitude spectrum of dump generated RF during a shot for which the DST was detuned in order to produce great RF power. The center frequency is f0=1.615 GHz, and the full width at 1/√2 of the maximum is df= 4.4 MHz (FHWM of power spectral line). These measurements yield a cavity quality factor of Q= f0/df =367.

The purpose of this article is to discuss yet another mechanism for RF generation in the dump. This source is periodic focusing of the electron beam by envelope oscillations of the mismatched ion beam produced by the electron beam interaction with the dump. Ion envelope oscillations with the correct wavelength are clearly evident in PIC code simulations of the dump region (Fig.2) [4]. The periodic ion-focusing from these oscillations would produce RF in the range of the strong cavity resonances predicted by Potter [3], and so is a prime candidate for the source of RF.

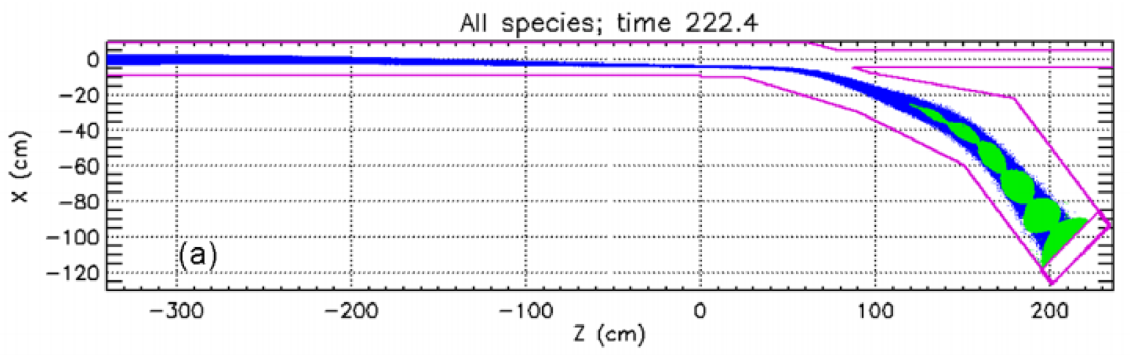

Figure 2: PIC code simulation of electron beam (blue) in the region of the DARHT Axis-II dump. Also shown (green) is the counter-streaming ion beam resulting from electron beam heating of the dump. The period of the ion beam envelope oscillations is ~21 cm, which would produce RF at ~1.4 GHz from periodic focusing of the electron beam.

Periodic focusing of an electron beam is an established means for generating RF and microwaves, focusing of an electron beam by an ion channel is a well known effect, periodic envelope oscillations of a mismatched beam is a familiar effect, and production of an ion beam by the interaction of an intense electron beam with a solid is a well-known effect. Taken together, these constitute a plausible mechanism for generation of RF in a range of frequencies that can fill the cavity of the dump and beam pipe. Although the PIC simulations are convincing, it would be enlightening to have an independent theoretical prediction of the ion envelope oscillations, with perhaps results that can be reduced to formulae easily applied in the laboratory. That is the purpose of this article. In Section II I present a brief theory based on envelope equations.

II. Envelope Theory

RF can be the direct result of ions backstreaming into the electron beam from the beam dump. The mechanism for RF production is as follows.

1. The 1.5-2.0 kA electron beam impacts the dump surface and desorbs gas; immediately by stimulated desorption, and later by thermal desorption as the surface is heated. Thermal desorption is the dominant mechanism once the surface is heated to ~ 300 C – 400 C, and the dominant gases are H2, O2, OH and H2O from sorbed water[5,6].
2. The desorbed gas is ionized by the incident beam through electron-impact ionization. Impact ionization cross-sections of desorbed gases are of order 10^{-16}cm^2 , and the density

of desorbed gas can be sufficient to supply space-charge limited ion currents within in a few ns of the surface reaching the critical temperature [5,6].

3. Positive ions are then accelerated upstream into the negative potential well formed by the electron beam space-charge. For our beam and the relevant geometry the space-charge depression is expected to be a few hundred kV.
4. This well also constitutes the confining (focusing) force for this counter streaming ion beam. It is unlikely that the ion beam will be perfectly matched to the electron focusing channel, and therefore it will undergo envelope oscillations.
5. The electron beam is itself focused by the ion beam. Therefore, the electron beam propagates through a periodic focusing field with period of the ion beam envelope oscillation wavelength. Periodically focused electron beams in resonant cavities are known to be strong sources of RF.
6. Moreover, focusing the electron beam accelerates the target heating and ionization process, generating even more ions, thus further boot-strapping the generation of RF.

This process could be the source of the observed RF, delayed to late in the pulse because of the time required to heat the surface to the critical temperature for strong desorption, and strongly amplified when the frequency determined by the ion-envelope oscillations coincides with the cavity frequency. Since protons from water desorption are prolific [5,6], only protons are considered in what follows (results can easily be generalized to other species if need be).

The period of the ion envelope oscillations can be determined using the envelope equation. Although the electron beam in the dump region is elliptical, for a first approximation one can consider round beams with equivalent cross-sectional area. In this approximation, the envelope equation for the counter-streaming ion beam can be written as

$$\frac{d^2 a_i}{dz^2} = \frac{K}{a_i} \tag{1}$$

The ion beam is neutralized by the electron beam, so the generalized perveance is

$$K = \frac{2I_i}{\beta_i^3 \gamma_i I_{0i}} \left(\frac{1}{\gamma_i^2} - f \right) \tag{2}$$

where the ion Alfven limiting-current constant is $I_{0i} = 4\pi\varepsilon_0 m_p c^3 / e \sim 31\text{MA}$. Anticipating that the ions are accelerated to only a few hundred keV, one can set $\gamma_i = 1$. Also, the fractional neutralization by electrons is $f = n_e / n_i > 1$ for space-charge limited ion current. Equation (2) can now be written as

$$\frac{d^2 a_i}{dz^2} = -k_0^2 a_i + \frac{K_0}{a_i} \tag{3}$$

where K_0 is the generalized perveance for an un-neutralized beam and

$$k_0^2 = \frac{2I_i}{\beta_i^3 I_{0i} a_i^2} f = \frac{e^2 n_e}{2\varepsilon_0 m_i v_i^2} \tag{4}$$

and we have used $I_i = n_i e \beta_i c \pi a_i^2$. Equation (3) explicitly shows that the ion beam is focused by the rigid electron beam background, and defocused by its own space charge.

The beam is matched to the focusing (all derivates equal zero) only if $f = 1$, which is not possible for space charge limited ion current, so the envelope will oscillate. As usual, we can reveal the natural period of this oscillate by considering small perturbations around the matched-beam envelope radius $a_{i0} = \sqrt{K_0} / k_0$. Setting $a_i = a_{i0} + \delta a$ in Eq. (3) and expanding to first order gives

$$\frac{d^2 \delta a}{dz^2} = -k_0^2 \delta a - \frac{K_0}{a_{i0}^2} \delta a = -2k_0^2 \delta a \tag{5}$$

with an oscillation wavenumber $k = \sqrt{2}\, k_0$ The ions are accelerated by the beam space-charge potential, which is proportional to the electron beam current [7], so the final ion kinetic energy is

$$\frac{1}{2} m_i v_i^2 = e\phi_{sc} = \frac{eI_e}{4\pi\varepsilon_0 \beta_e c} \tag{6}$$

This energy is at most few hundred keV, confirming the approximation $\gamma_i \sim 1$, and Eq. (4) becomes

$$k_0^2 = \frac{e^2 n_e}{4\varepsilon_0 [e\phi_{sc}]} = \frac{1}{a_e^2} \tag{7}$$

which depends <u>only</u> on the geometry of the electron beam. Thus, the wavelength of the oscillation is $\lambda = 2\pi / k = \sqrt{2}\, \pi a_e$, and the RF frequency resulting from this periodic focusing would be $f = 6.8(\text{GHz}) / a_e(\text{cm})$. Although this estimate has been derived for a round beam, it should provide an approximate answer for an elliptical beam if one substitutes $a_e = \sqrt{a_e b_e}$. For example, based on input from LANL, Humphries uses a nominal 5:1 ellipse with nominal area of 25cm^2 for his heating calculations [8]. The corresponding effective radius would be 2.82 cm, and the RF frequency would be 2.4 GHz. So even with twice the footprint, the frequency would be 1.7 GHz. Humphries calculates surface temperature rises of more than 300C for electron beam density with 25-cm^2 area, so it is reasonable to assume sufficient ion production to supply a space-charge limited ion current [5,6] from a slightly over-focused beam that produces RF.

It was earlier asserted that the maximum ion density, that produced by a space-charge limited ion current, ensured that $f = n_e / n_i > 1$. To show this, the relevant ion current density is obtained exactly as the Child-Langmuir space-charge limit, with the electron space charge providing the applied voltage. The space-charge limit for protons is

$$j_i = n_i e v_i = \frac{4}{9}\varepsilon_0 \sqrt{2e/m_p}\,\frac{\phi_{sc}^{3/2}}{z_m^2} \tag{8}$$

where z_m is the distance from the surface to the electron space charge potential minimum. Eliminating the velocity by conservation of energy ($m_i v_i^2/2 = e\phi_{sc}$) gives the ion density

$$n_i = \frac{4\varepsilon_0}{9e}\frac{\phi_{sc}}{z_m^2} \tag{9}$$

Substituting the space-charge potential from Eq. (6) gives an expression for f :

$$f = \frac{n_e}{n_i} = 9\frac{z_m^2}{a_e^2} \tag{10}$$

The dominant term in the Bessel expansion for the potential inside a finite cylinder of charge (the relevant problem for a cylindrical electron beam impacting a target) is proportional to $J_0(x_{01} r / a_e)\tanh(x_{01} z / a_e)$, where $x_{01} = 2.4$ is the first zero of J_0. The hyperbolic tangent is 0.96 for a value of 2, and 0.995 for a value of 3, which would be close to the maximum acceleration of the ions. Using $z = 3a_e / 2.4$ as an estimate for z_m gives $f = 14$, thereby justifying the assumption.

III. Conclusions

The envelope theory used to understand the results of the PIC code calculation shown in Fig. 2 is obviously only an approximation, but it does lend credence to the model of periodic focusing of the electron beam with a wavelength that falls in the range of the observed RF, and also in the range of the predicted resonant frequencies of the dump and beam pipe. For more accuracy, one should clearly use beam simulations in the appropriate geometry. These are forthcoming, and will be the subject of a future report on this topic.

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